ATLAS results on exotic hadronic resonances

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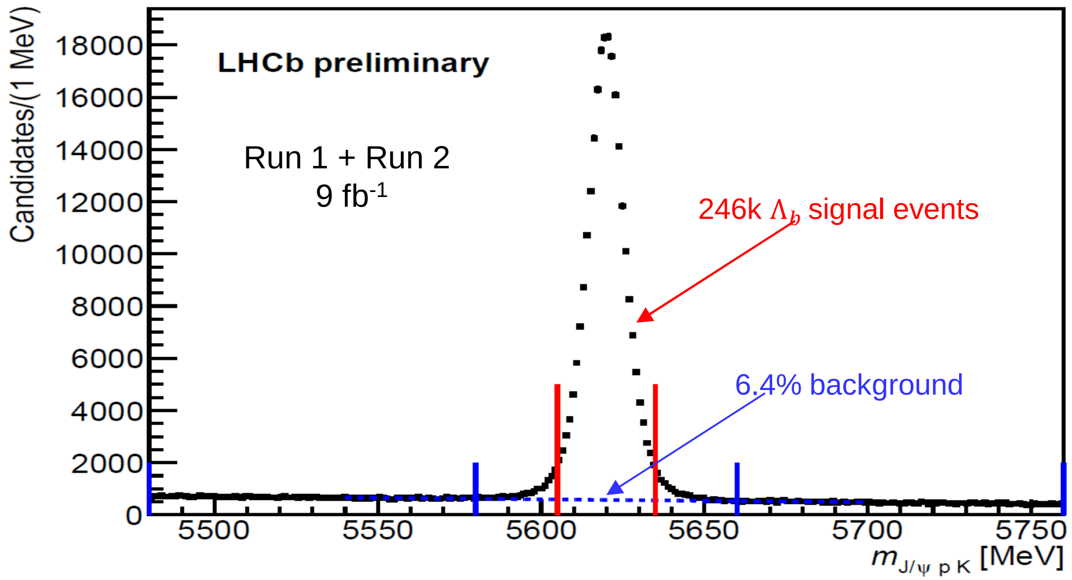
on behalf of the ATLAS Collaboration

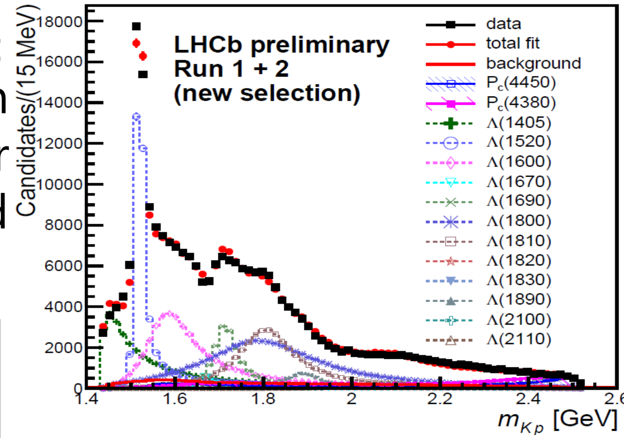
- Pentaquarks discovery at LHCb and subsequent studies
  - Λ_b candidate selection at ATLAS
  - $H_b \to J/\psi hh$ decay models
  - $\Lambda_b \to J/\psi pK$ Signal region analysis
- Analysis of resonances in di-J/ψ spectrum
  - Discovery of X-6900 signal at LHCb
  - ATLAS results in di-J/ψ and $J/\psi, \psi(2S)$ *channels* and plans
- Conclusions

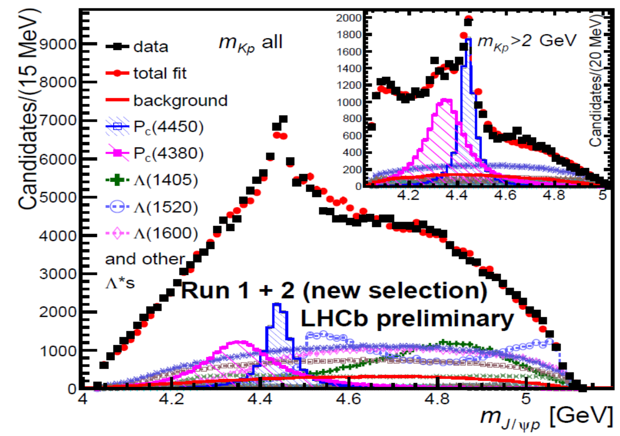
ATLAS results on pentaquarks in $\Lambda_b \to J/\psi p K$ decays

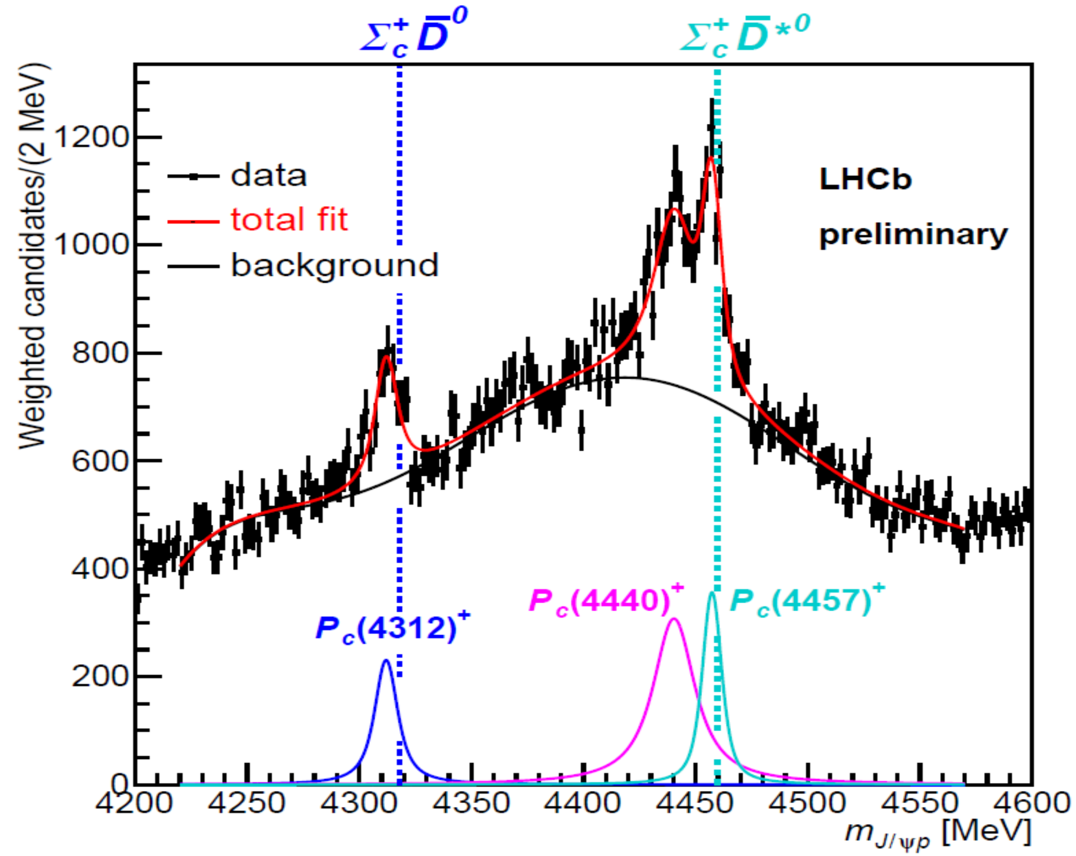
Pentaquark states discovery

Two states $P_c(4380)$ and $P_c(4450)$ discovered at LHCb in 2015.With Run II data providing ~9x statistics of Run I for $\Lambda_b \to J/\psi pK$ decays (246K candidates) LHCb published new results:









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State $P_c(4450)$ revealed substructure: two states $P_c(4457)$, $P_c(4440)$. New $P_c(4312)$ is observed.

Run II analysis methods **were not sensitive** to the wide $P_c(4380)$ state.
Broad structures in $J/\psi p$ can potentially be just a reflection of Z_{cs} states in $J/\psi K$ final states.

Reconstruction of $\Lambda_b \to J/\psi pK$ candidates at ATLAS

1. Due to absence of hadron track identification, we select $J/\psi, h_1, h_2$ candidates, where h_1, h_2 are hadrons of unknown flavour: p, K, π;

2. We had to perform simultaneous analysis of kinematically close Λ_b, B_d and B_s decays:
   - $\Lambda_b \to J/\psi, p, K$ via variuos Λ^* or P_c states
   - $B^0 \to J/\psi, K, \pi$ via various K^* or exotic Z_c states
   - $B^0 \to J/\psi, \pi, \pi$
   - $B_s \to J/\psi, K, K$ via variuos f and φ states
   - $B_s \to J/\psi, \pi, \pi$

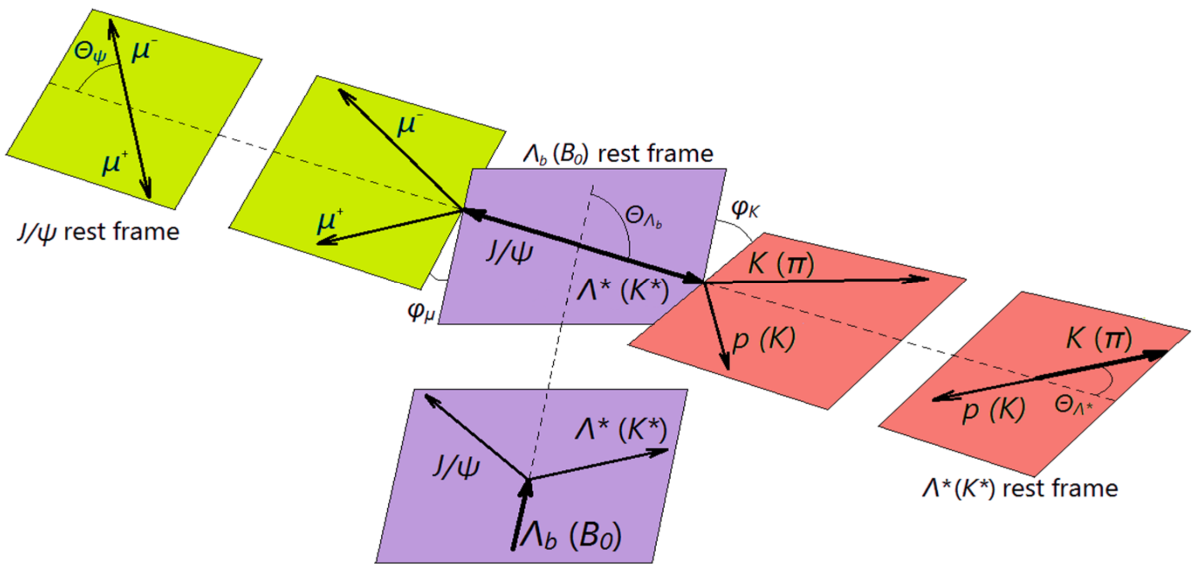
3. Simulation of $\Lambda_b \to J/\psi, p, K$; $B^0 \to J/\psi, K, \pi$; $B_s \to J/\psi, K, K$ processes uses phase space decay events weighted by theoretically calculated matrix elements;

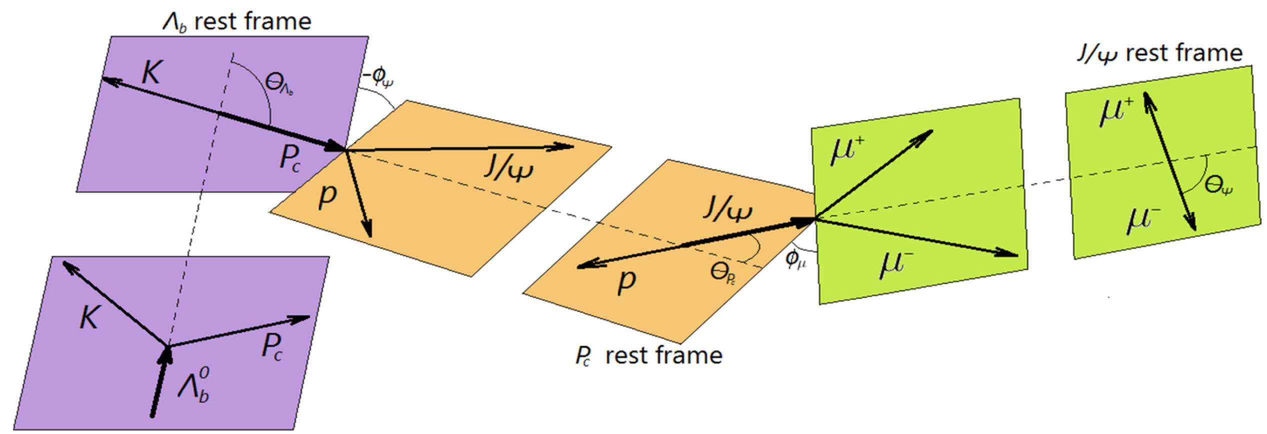
4. To suppress high backgrounds from light Λ^*, K^*, f, φ states as well as combinatorial background, only events with high $M(h,h)$ are selected: $M(K,\pi)$ and $M(\pi,K) > 1.55$ GeV → $M(p,K) \gtrsim 2$ GeV;

$\Lambda_b \to J/\psi, p, K$ decays simulation

- Helicity amplitudes are used to calculate weights to model differerent decay channels on top of the phase space MC
- Reduced model has only 1 complex coupling for each Λ^*; while full matrix element for pentaquark signals (5 complex coupling constants each);
- Extended model (which coincides with LHCb "reduced" model) includes more terms for $\Lambda^*(1800)$, $\Lambda^*(1810)$, $\Lambda^*(1890)$;

	Spin/parity	Number of couplings (extended)	Number of couplings (simplified)	Number of couplings (full model)
$\Lambda^*(1800)$	$1/2^-$	4	1	4
$\Lambda^*(1810)$	$1/2^+$	3	1	4
$\Lambda^*(1820)$	$5/2^+$	1	1	6
$\Lambda^*(1830)$	$5/2^-$	1	1	6
$\Lambda^*(1890)$	$3/2^+$	3	1	6
$\Lambda^*(2100)$	$7/2^-$	1	1	6
$\Lambda^*(2110)$	$5/2^+$	1	1	6
P_c	$1/2$	4	4	4
P_c	$>1/2$	5	5	5

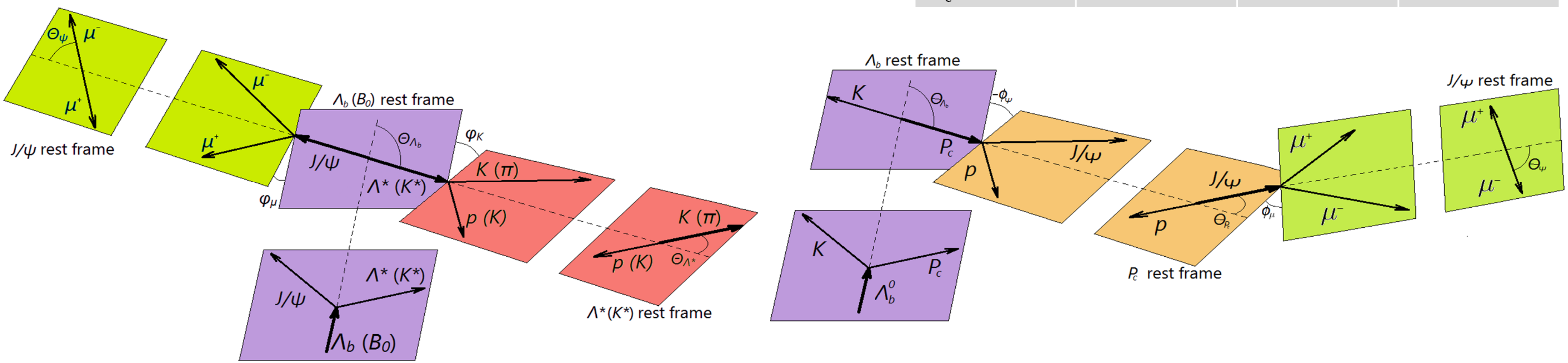




$B^0 \to J/\psi, K, \pi$; decays simulation

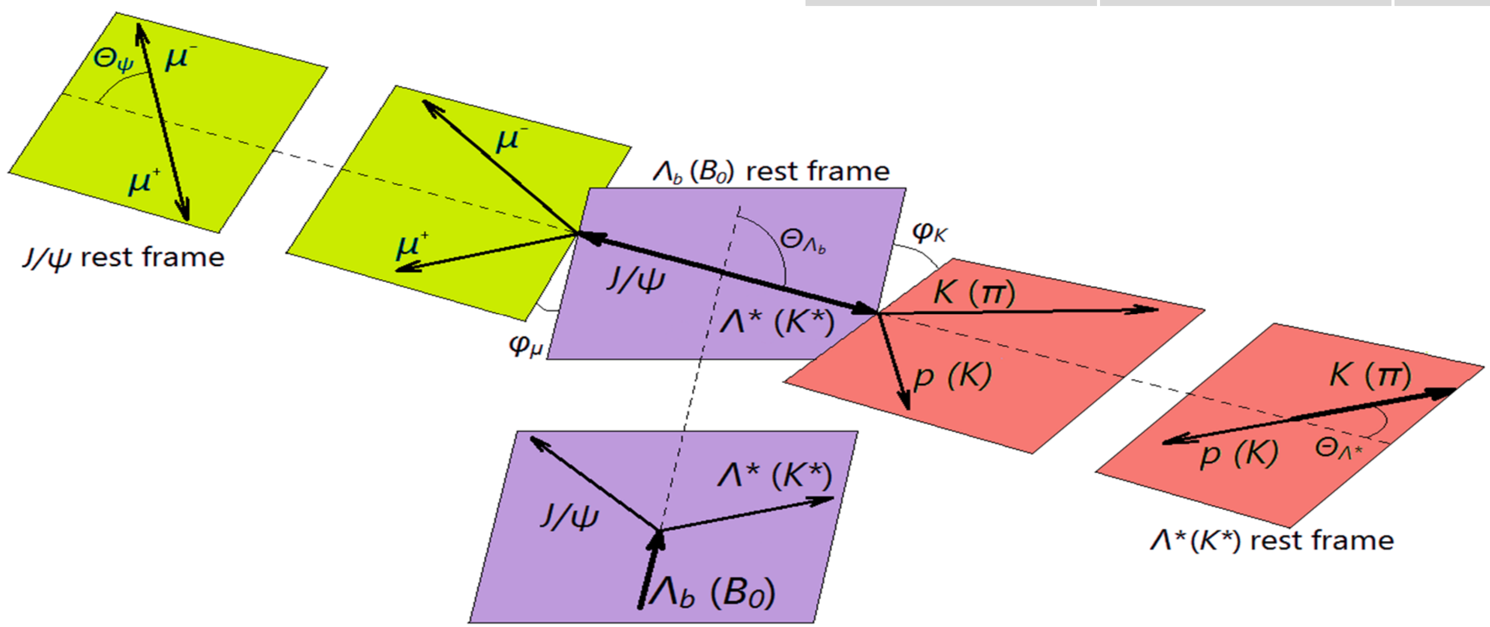
- Full theoretical model includes 3 complex couplings for each K^* with spin >0;
- Reduced model has only 1 complex coupling for each K^*
- Extended model for $B^0 \to J/\psi, K, \pi$ decays is used. The 'reduced' model is incapable in describing data
- Exotic $\boldsymbol{Z_c(4200)}$ state is included into B^0 decay model. **Its contribution is considered as systematic effect**

	Spin/parity	Number of couplings (extended)	Number of couplings (reduced)
$K^*(1410)$	1^-	3	1
$K^*(1430)$	0^+	1	1
$K^*(1430)$	2^+	3	1
$K^*(1680)$	1^+	3	1
$K^*(1780)$	3^-	3	1
$K^*(1950)$	0^+	1	1
$K^*(2045)$	4^+	1	1
$Z_c(4200)$	$1^+,2^-,3^+$…	2	2
$Z_c(4200)$	$0^-,1^-,2^+$…	1	1



1. Full theoretical model includes 3 complex couplings for each φ or f state with spin >0;
2. Reduced model has only 1 complex coupling for each resonance;
3. We use **extended model** to describe data in B_s CR.

	Spin/parity	Number of couplings (extended)	Number of couplings (reduced)
$\varphi(1680)$	1^-	3	1
$f_2(1525)$	2^+	3	1
$f_2(1640)$	2^+	3	1
$f_2(1750)$	2^+	3	1
$f_2(1950)$	2^+	3	1



Reconstruction of $H_b \to J/\psi hh$ candidates

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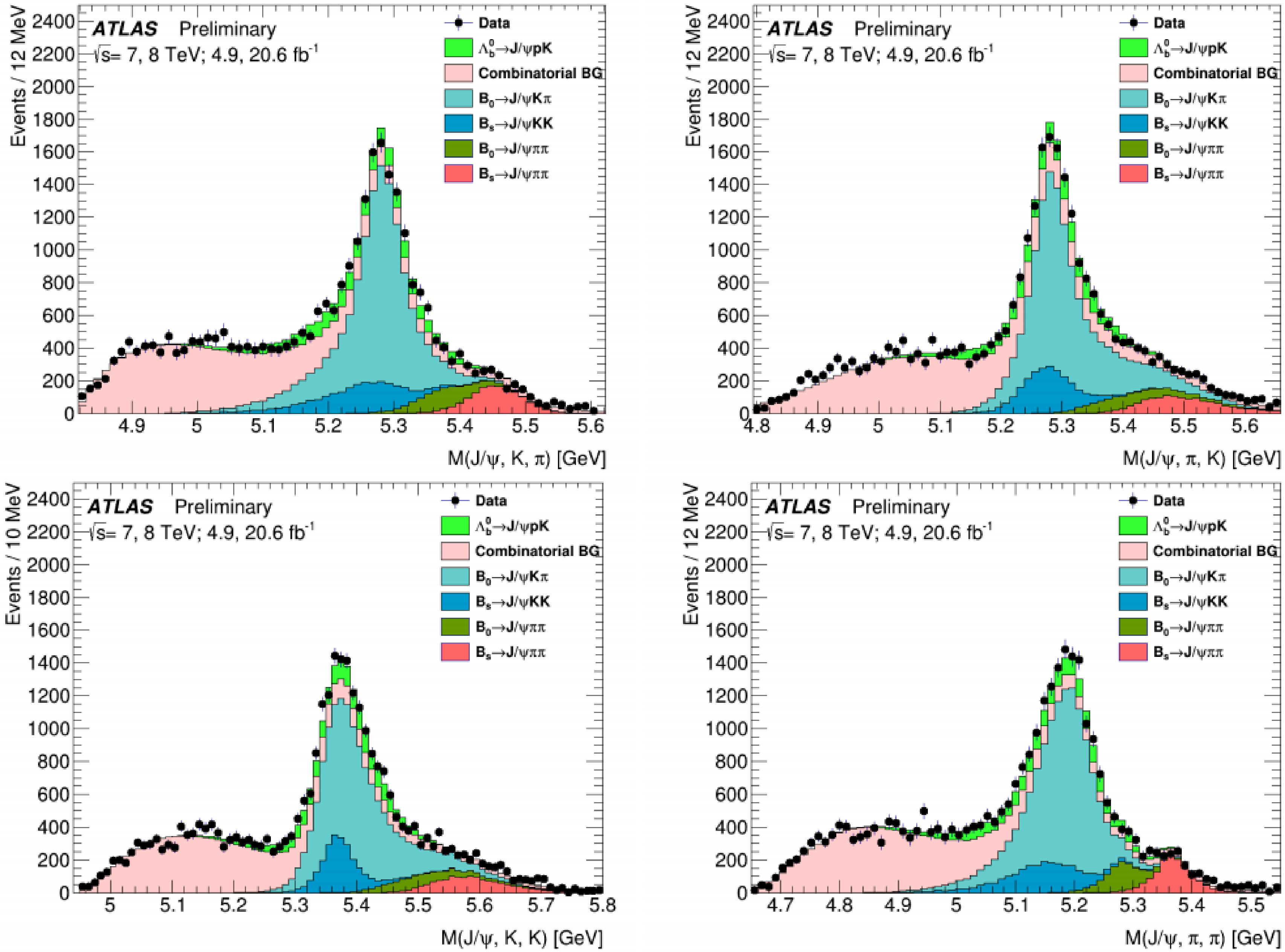


Selected events are analyzed simultaneously with different hadrons mass assignments.

This provides sensitivity to all processes contributing to our kinematic region…

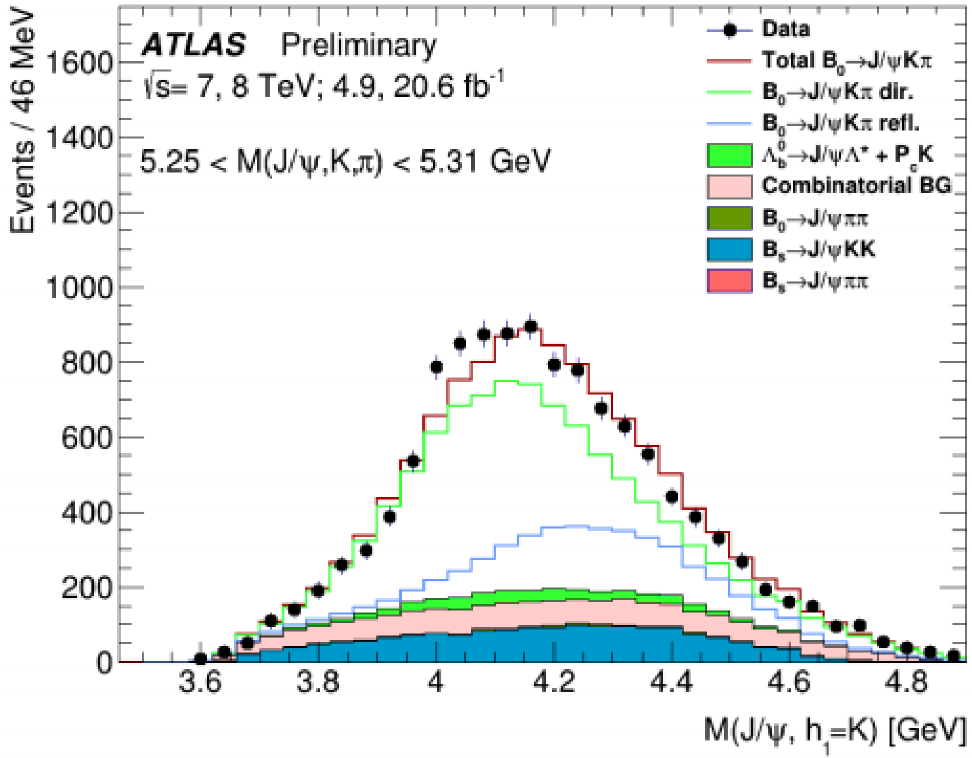
Different decays yields obtained from fits to data:

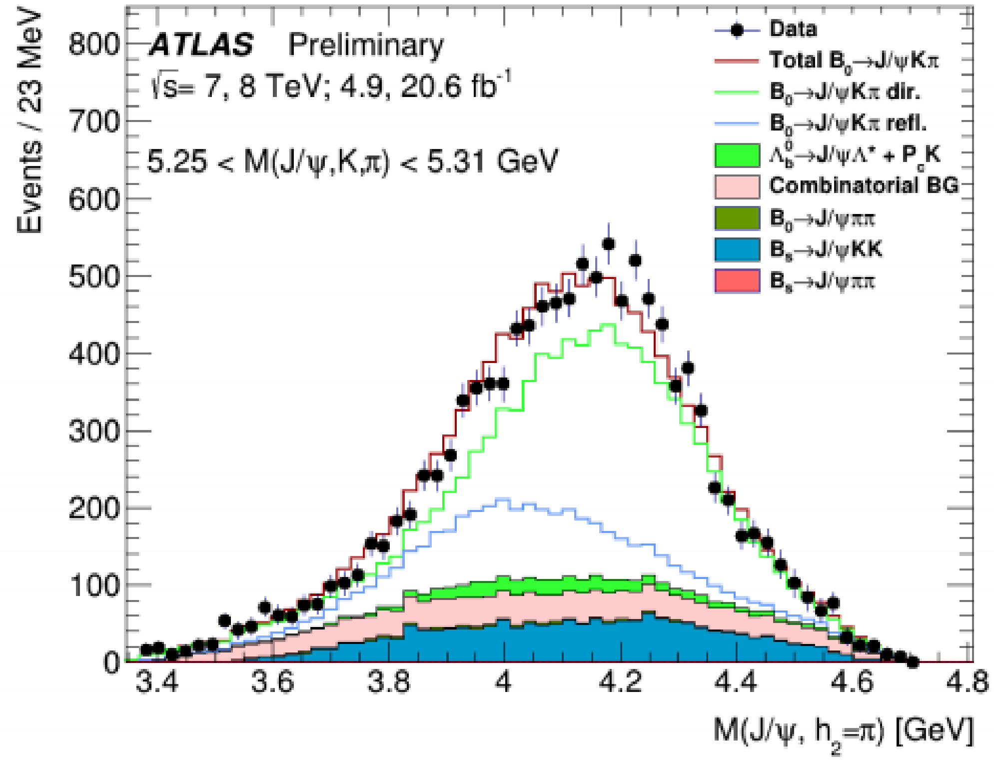
$N(\Lambda_b \to J/\psi pK) = 2270 \pm 300$
$N(B^0 \to J/\psi K\pi) = 10770$
$N(B_s \to J/\psi KK) = 2290$
$N(B^0 \to J/\psi \pi\pi) = 1070$
$N(B_s \to J/\psi \pi\pi) = 1390$

B-meson control region

ATLAS-CONF-2019-048

We analyzed ~10K $B^0 \to J/\psi K\pi$ decays with Run I data w.r.t. properties of intermediate states. Data description without exotic contributions is not perfect (right plot) and demonstrates hints on $Z_c^+(4200)$ contributions.





- Plots show M($J/\psi K$), M($J/\psi\pi$) distributions in the B^0-meson signal region;
- Z_c(4200) contribution is considered as systematics w.r.t. pentaquark parameters measured;
- With Run II data ~5 times more signal candidates are reconstructed with smaller systematic from other processes parameters; also, angular information to be included to gain sensitivity to the spin-parity; **Run II analysis is ongoing…**

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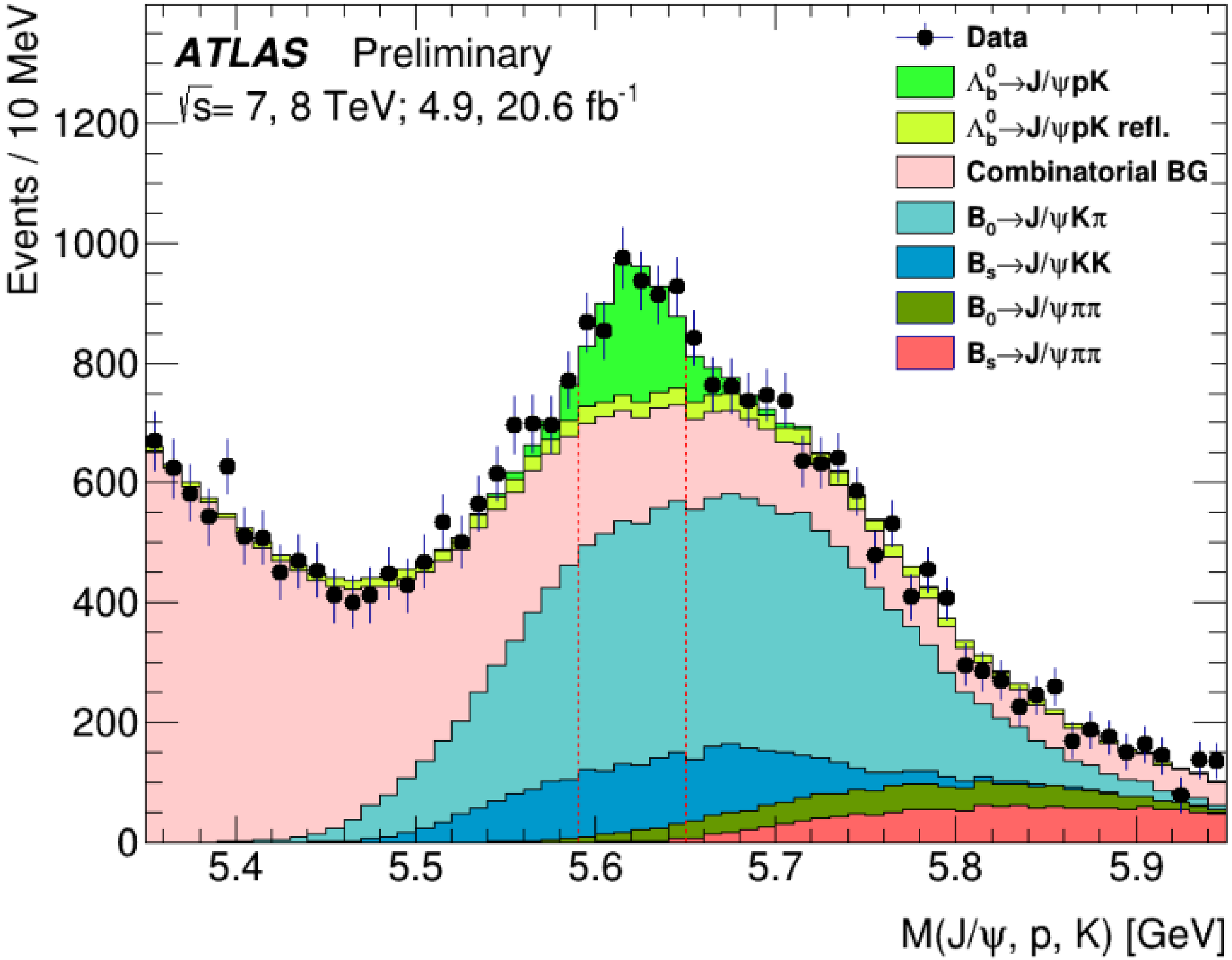


Total number of $\Lambda_b \to J/\psi pK$ candidates selected is **2270±300**

Green histogram shows Λ_b signal with correct mass assignment;
Yellow histogram shows Λ_b signal with wrong mass assignment;

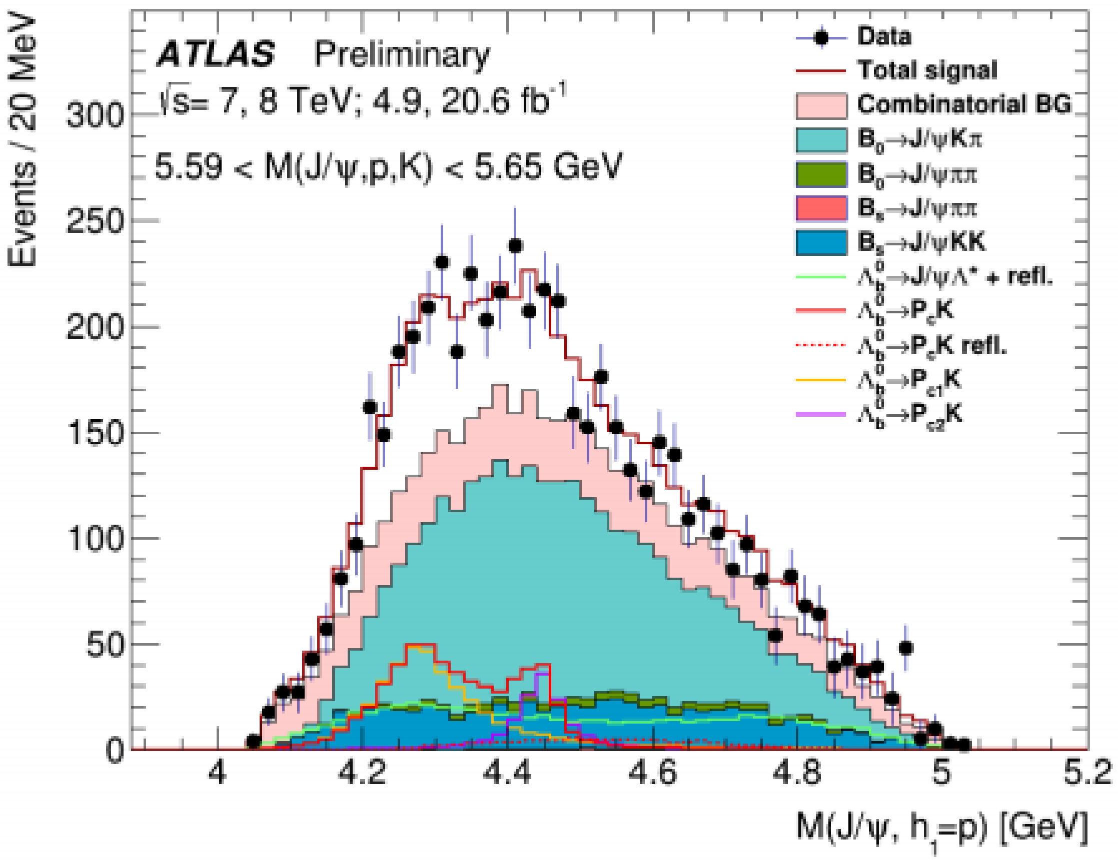
Signal region include events with:
5.59GeV < M($J/\psi pK$) < 5.65GeV OR
5.59GeV < M($J/\psi Kp$) < 5.65GeV

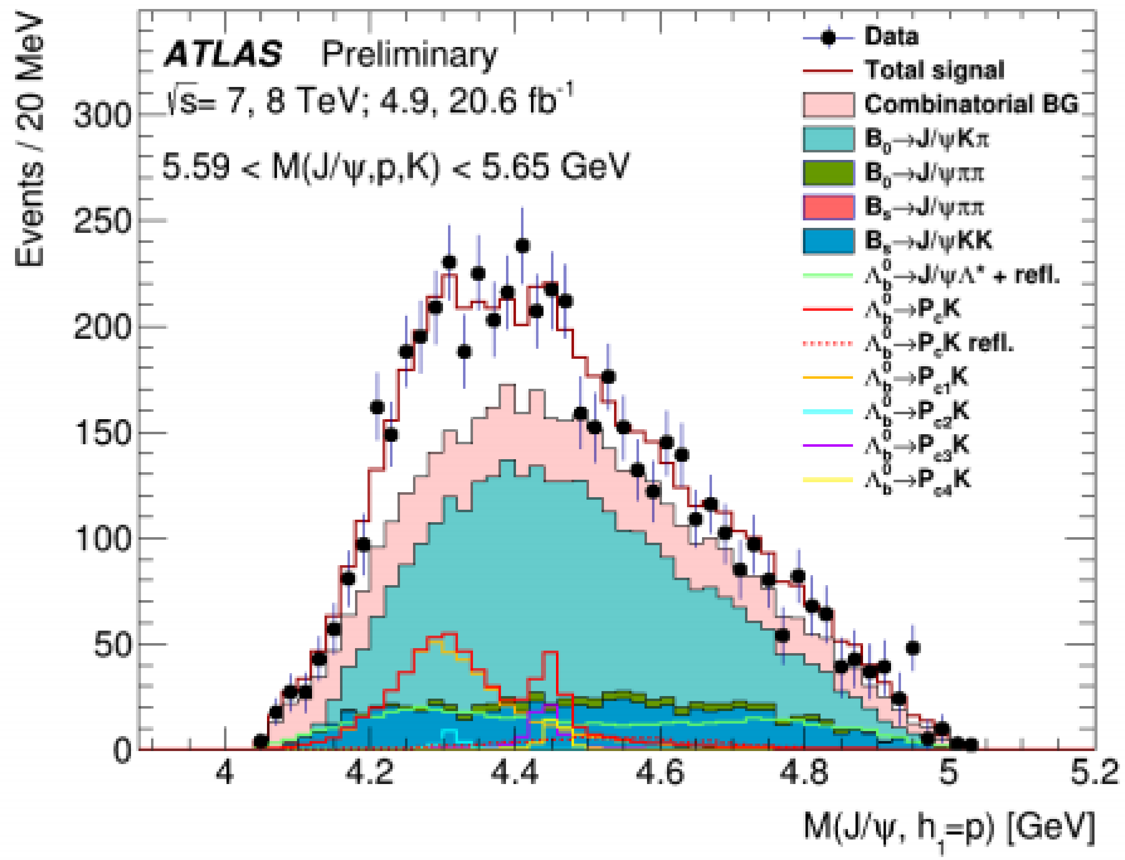
In the signal region there are:
***$N(\Lambda_b \to J/\psi pK)$*=1010±140**
signal candidates with correct mass assignment

Pentaquark studies at ATLAS experiment

In the **2 pentaquark** hypothesis (left plot), parameters of 2 pentaquarks are consistent with those measured by LHCb in 2015. **4 pentaquark** hypothesis (following LHCb 2019 result, right plot) is also consistent with ATLAS data;
P_c(4380) state is questioned…
4 P_c model result is included into systematics for P_c(4380)

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV





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Testing models without P_c states

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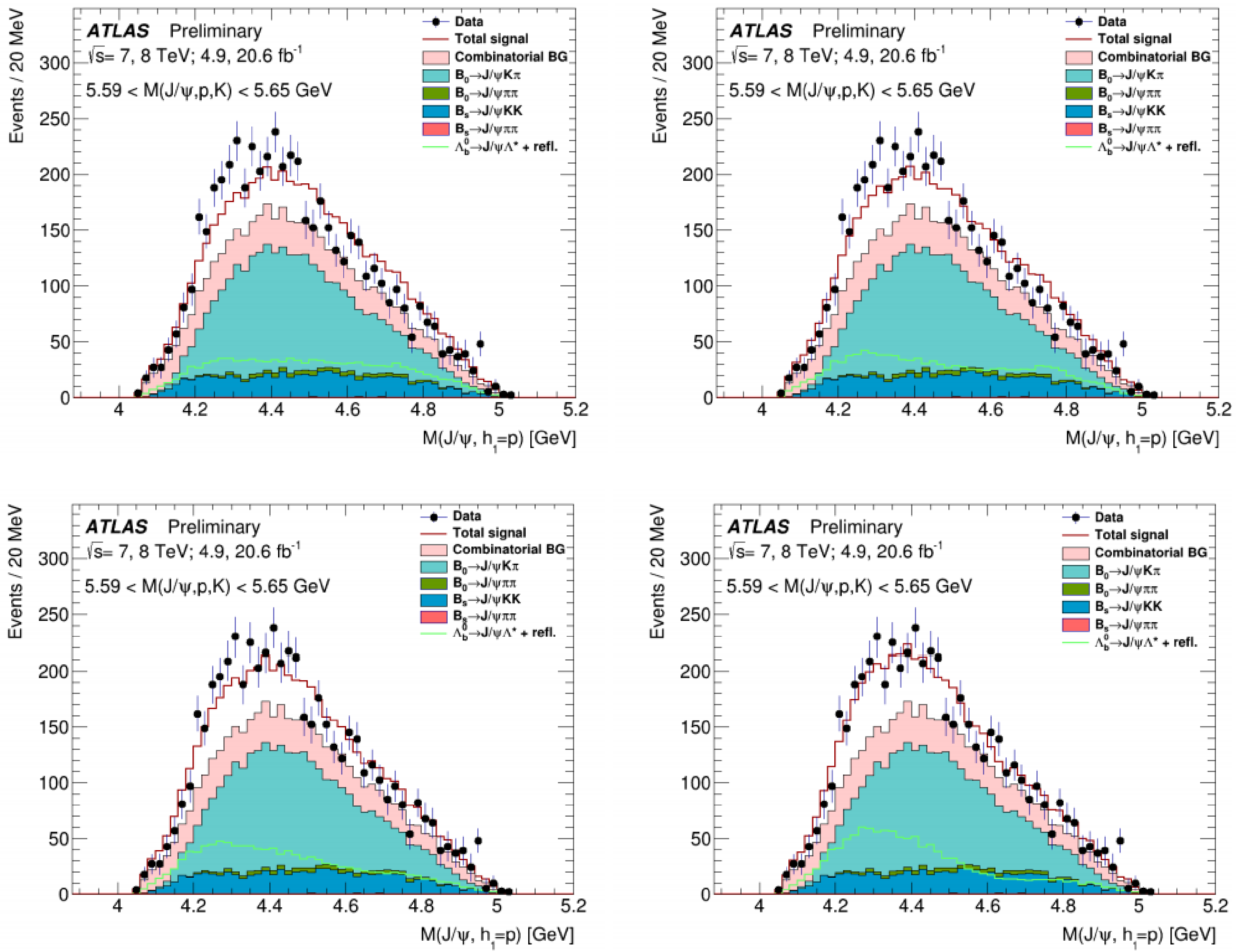


Plots show different models without exotic contribution.

Top left: fit of M(*J/ψp*), M(*J/ψK*), *M(p,K)* with minimal $\Lambda_b \rightarrow J/\psi \Lambda^*$ decay model.

Bottom left: fit of M(*J/ψp*), M(*J/ψK*), *M(p,K)* with extended $\Lambda_b \rightarrow J/\psi \Lambda^*$ decay model.

Top right: fit of M(*J/ψp*) with minimal $\Lambda_b \rightarrow J/\psi \Lambda^*$ decay model.

Bottom right: fit of M(*J/ψp*) with extended $\Lambda_b \rightarrow J/\psi \Lambda^*$ decay model.

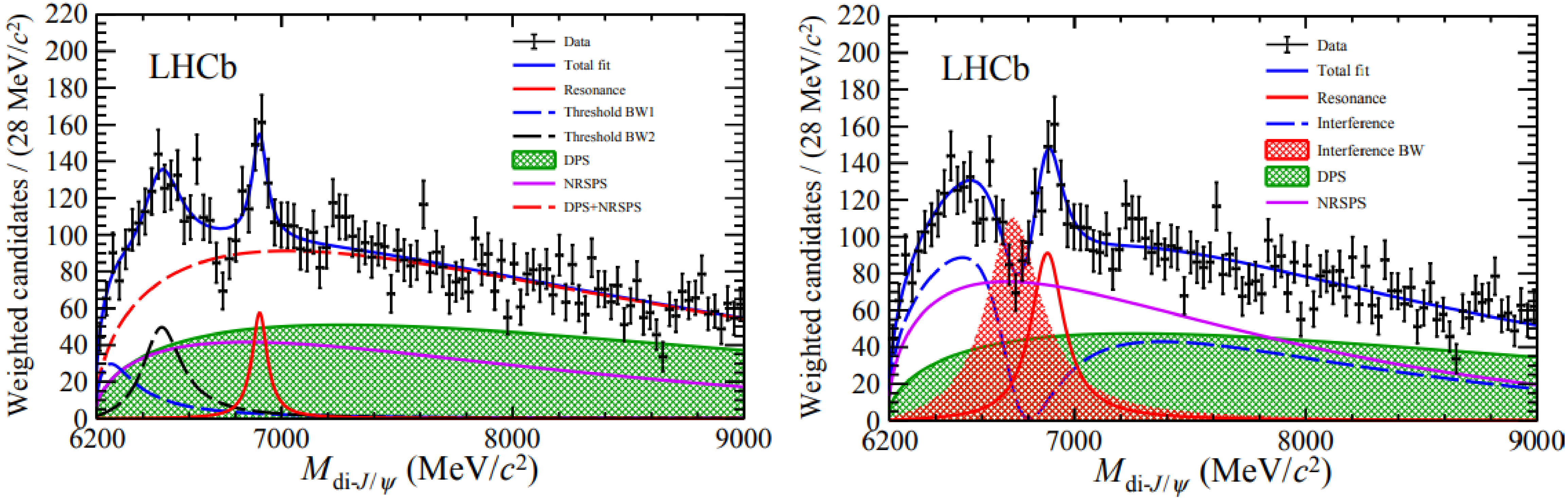
Maximal *p*-value found for the no-*Pc* models is $9.1 \cdot 10^{-3}$

- Analyses of exotic states are ongoing with ATLAS Run II data;
- For pentaquark analysis – signal candidates statistics, detector mass resolution and precision of background modeling are critical;
- Amplitude analysis is needed to confirm/disclaim wide $P_c(4380)$ state;
- Z_{cs} states can contribute to $\Lambda_b \to J/\psi pK$ decays and conqer wide pentaquark…
- Pentaquarks with strangeness (discovered in 2020) and naturally expected from QCD neutral pentaquarks can be searched in ATLAS data;
- Its also interesting to test D0 results for inclusive production of pentaquarks;

- Studies of the Z_c and Z_{cs} state are ongoing with ATLAS Run II data;

ATLAS results on J/ψ pair production and $X(6900)$ studies

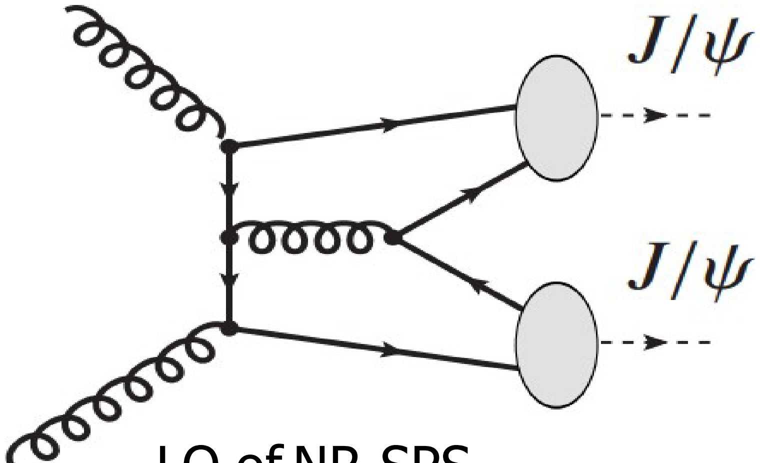
 Science Bulletin 65 (2020) 1983



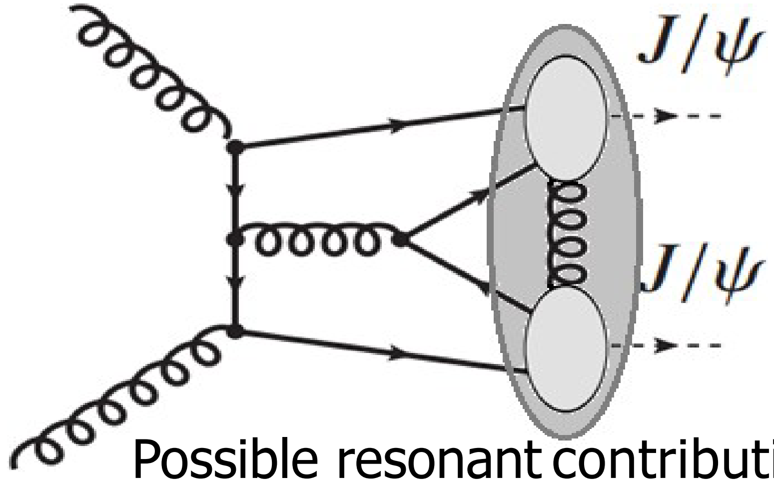
Study of J/ψ pair production at LHCb revealed resonant-like structures near production threshold. Prominent signal (sig. > 5σ) is observed at 6.9GeV, compatible with hypothesis of di-charmonium tetraquark. Accounting for interference between non-resonant background and signal (right plot) improves data description. In this model, parameters of the signal measured are:

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\mathrm{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\mathrm{MeV}.$$

Signal and backgounds



LO of NR-SPS



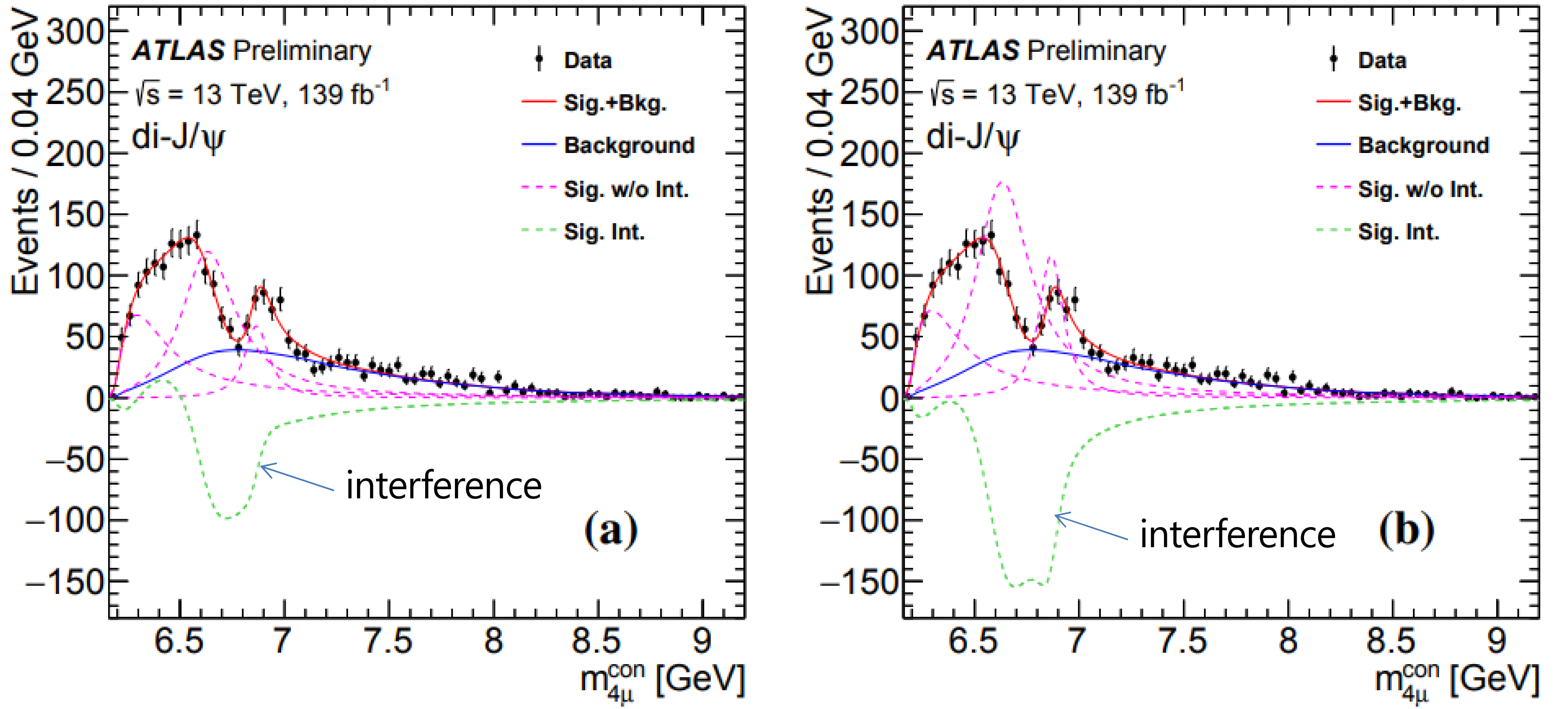
Possible resonant contribution

+ higher order processes with, e.g., additional light jets or c-jets in the final state

- There are basically two mechanisms of di-J/ψ production: SPS (Single Parton Scattering) and DPS (Double Parton scattering);
- Possible resonant production is (very likely) related to SPS mechanism (see diagrams);
- Interference effects are expected between NR-SPS and signal, thus, in case spin-parity measurement of the possible resonance, one needs to sum up amplitudes for these processes coherently;
- Threshold effects are expected near the di-J/ψ threshold and interfere with NR-SPS background;
- DPS (similar to combinatorial bkg) and can be well modeled using, e.g., event mixing approach;

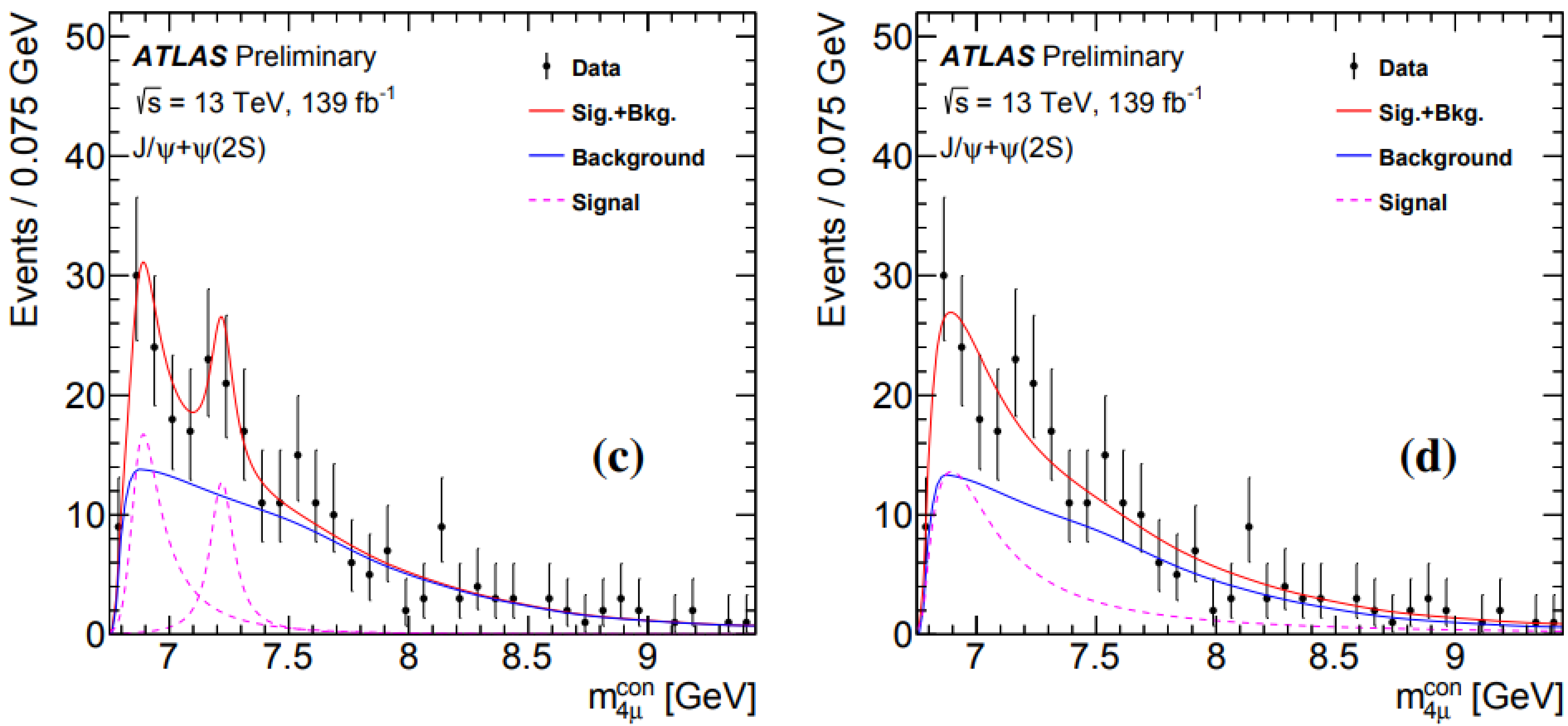
Studies of J/ψ pair production: ATLAS results

ATLAS-CONF-2022-040



- Analysis of di-J/ψ spectrum in ATLAS data led to two degenerate solutions.
- Fits feature same likelihood but different resonant amplitudes as well as interference plays differently in two cases.
- Significance of the $X(6900)$ contribution is estimated at the level of 10σ.

ATLAS-CONF-2022-040



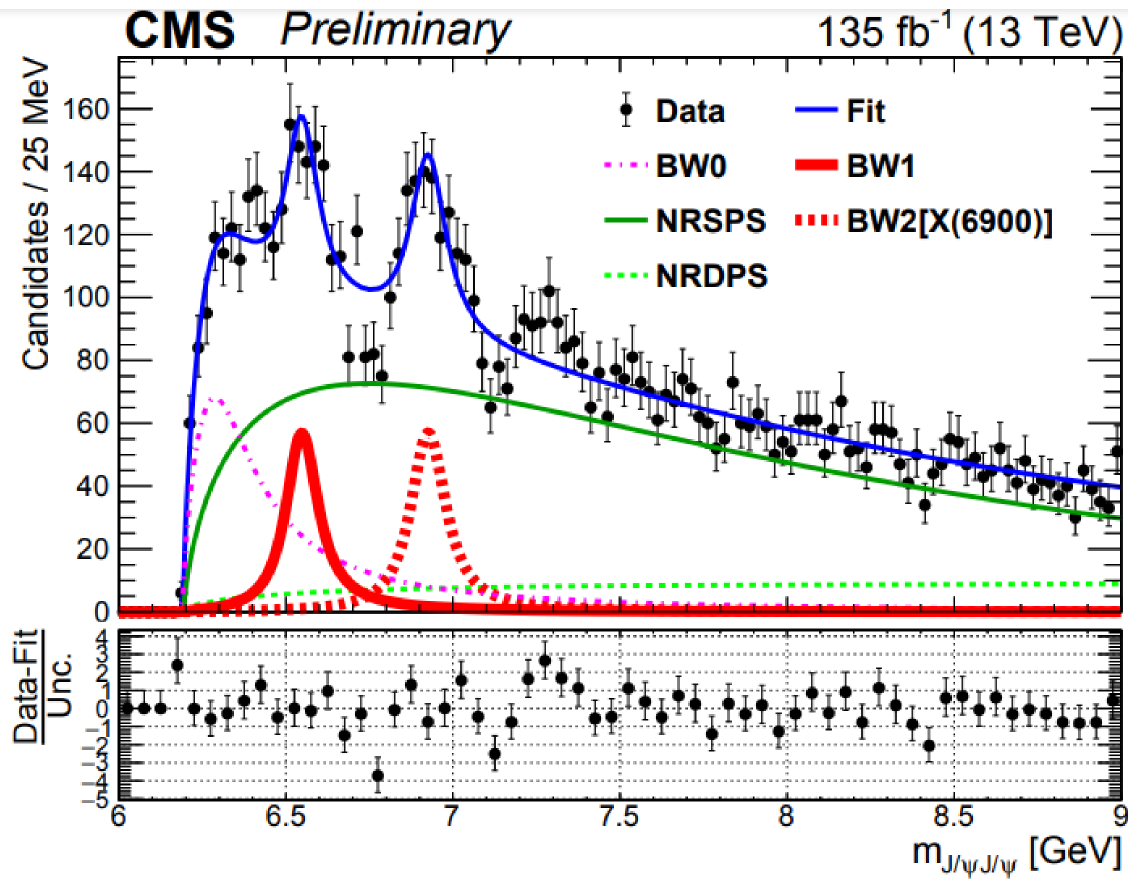
- Analysis of *J/ψ ψ(2S)* spectrum confirms *X*(6900) contribution and gives hint on the contribution from resonance between 7.2-7.3 GeV.
- Significance of both contributions is estimated at level of 4.6σ.

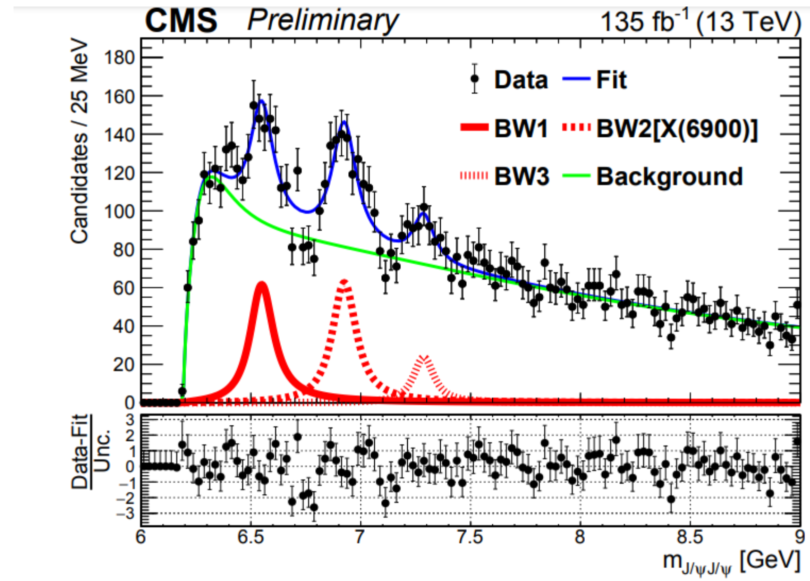
 ATLAS-CONF-2022-040

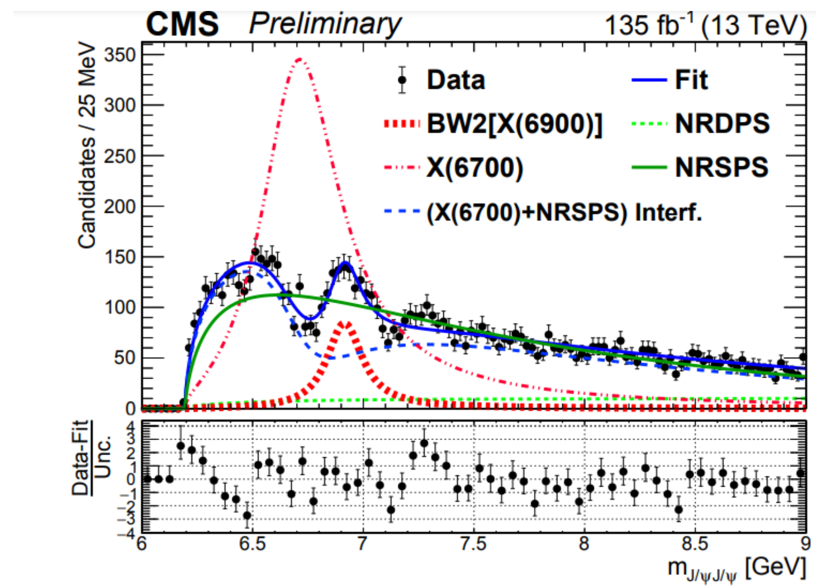
(GeV)				
	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	
(GeV)		m_3	Γ_3	
J/ψ+$\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$	—
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$	—

- Parameters of the three signals in the di-*J/ψ* channel are shown in the top of the table;
- For *J/ψ*, *ψ(2S)*, two models are considered. Model A includes four states with parameters of the three of them being fixed to the di-*J/ψ* channel results. Model B include just one resonant signal with free parameters.

CMS-PAS-BPH-21-003

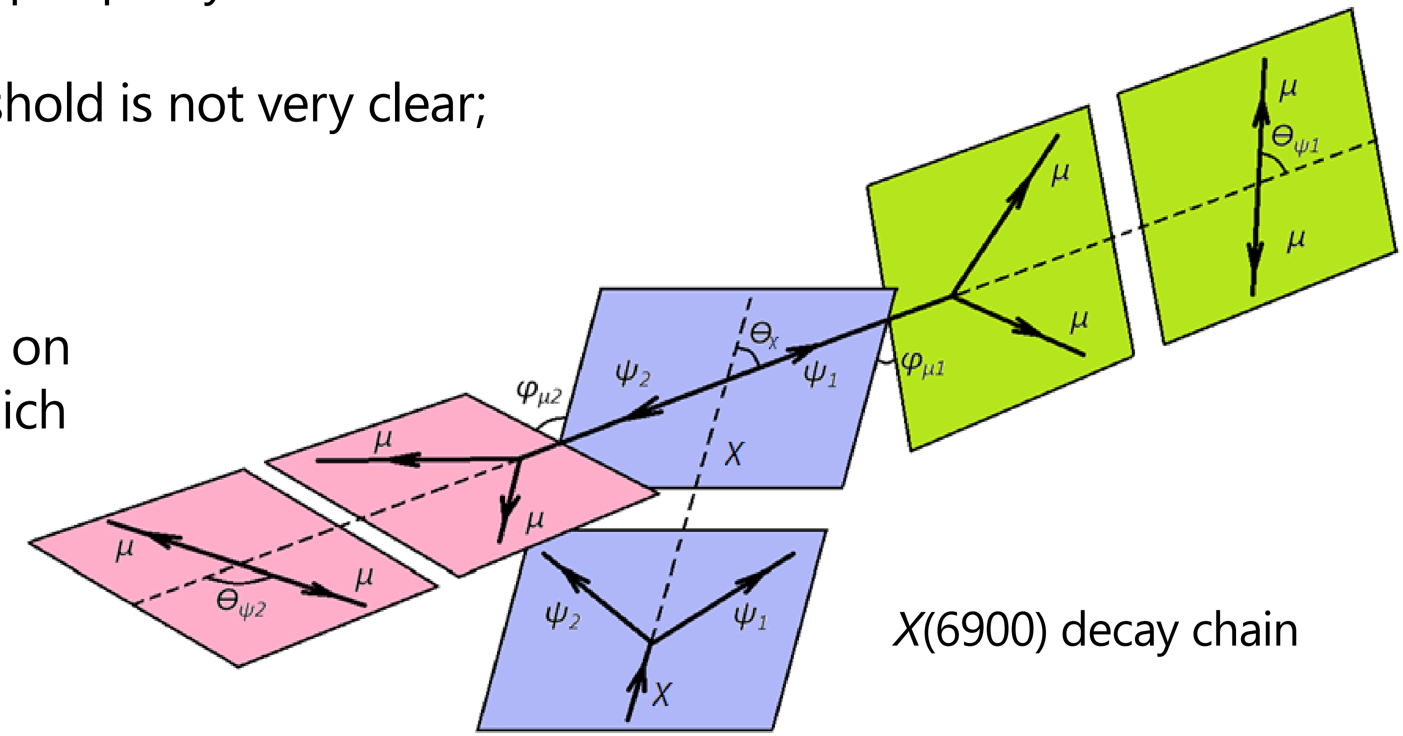






- Analysis of *J/ψ* pair spectrum confirms *X*(6900) contribution and also gives hint on the contribution from resonance near 7.3 GeV.
- M_1 = 6927 ± 9(stat) ± 5(syst) MeV, local significance > 5σ
- M_2 = 6552 ± 10(stat) ± 12(syst) MeV, local significance > 5σ
- M_3 = 7287 ± 19(stat) ± 5(syst) MeV, local significance 4.1σ

- Amplitude analysis is ongoing with ATLAS data for the signals observed in di-J/ψ channel; this will allow precise analysis of the observed signals including angular information;
- Decay kinematics of X(6900) include 5 independent angular variables;
- θ_X is anticipated to carry sensitivity to spin-parity of resonances;
- Nature of the broad structures at threshold is not very clear;
- LHCb, CMS and ATLAS data show hint on the additional signal at 7.2-7.3GeV, which needs further analysis;



X(6900) decay chain

Conclusions

- Run I pentaquark analysis showed results consistent with LHCb and motivated further studies of tetraquark and pentaquark states with new data.

- Few analysis of exotic states in B-hadron decays are ongoing…

- Study of J/ψ pair production revealed resonant-like signal at ~6.9GeV. Precise analysis is needed to shed light on properties of the signal and region close to threshold.

Thanks for your attention!

BACKUP

$\Lambda_b \rightarrow J/\psi,p,K$ candidate selection at ATLAS

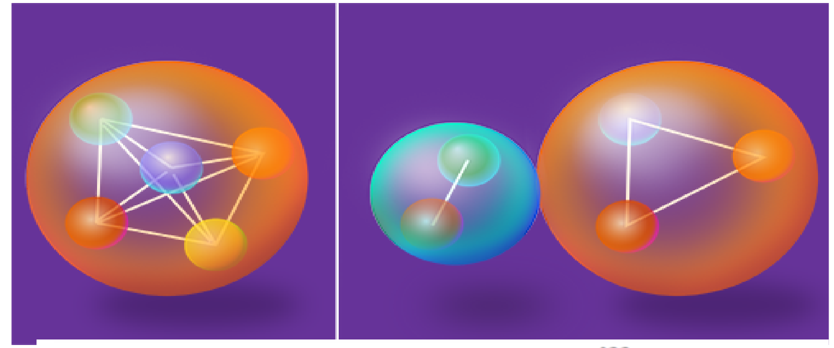
1. Muon pairs for J/ψ candidates selected with muon triggers;
2. 2 muons passing MCP selection rules, coming from J/ψ decay (3097 ± 290 GeV);
3. 2 muon tracks + 2 hadron tracks simultaneously fit to common vertex (dimuon mass constrained to J/ψ mass) and Λ_b candidate track to primary vertex with $\chi^2/NDF<16/8$;
4. 2 hadron tracks, (each of them can be assigned different mass hypotheses (proton, kaon, pion);
5. $p_T>2.5$ GeV for proton candidate and $p_T>1.8$ GeV for kaon candidate, having at least 2 hits in Pixel and 6 hits in SCT;
6. Transverse decay length $L_{xy}(\Lambda_b)>0.7$mm;
7. $p_T(\Lambda_b)/\Sigma p_T$(track) > 0.2, where sum is taken for all tracks originating from PV;
8. $p_T(\mu^\pm)$ > 4GeV, $|\eta(\mu^\pm)|<2.3$, $p_T(\Lambda_b)$ > 12GeV, $|\eta(\Lambda_b)|$ < 2.1;

9. Inv. mass of hadron tracks (in $K\pi$ and πK mass hypotheses): $M(K\pi)$ > 1.55 GeV and $M(\pi K)$ > 1.55 GeV: to suppress decays via light intermediate K^*, Λ^* and other resonances;
10. $\cos\theta^*$ between proton and $J/\Psi\ p$ system in $J/\Psi\ p$ rest frame > -0.5;
11. $\cos\theta^*$ between kaon and Λ_b candidate in Λ_b candidate rest frame > -0.8;
12. $|\cos\theta^*|$ between kaon and Λ^* in Λ^* rest system less than 0.85;
13. Events for $J/\psi p$ signal search are taken in window $M(J/\psi pK)$ = 5620 ± 30 MeV;
14. Subtraction of distributions with two same sign hadron tracks is applied;

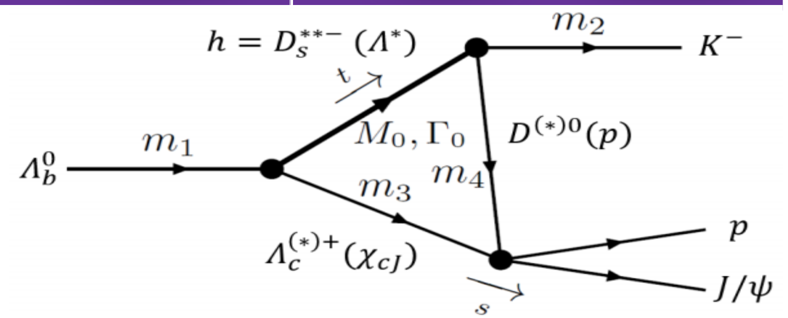
Pentaquark structure

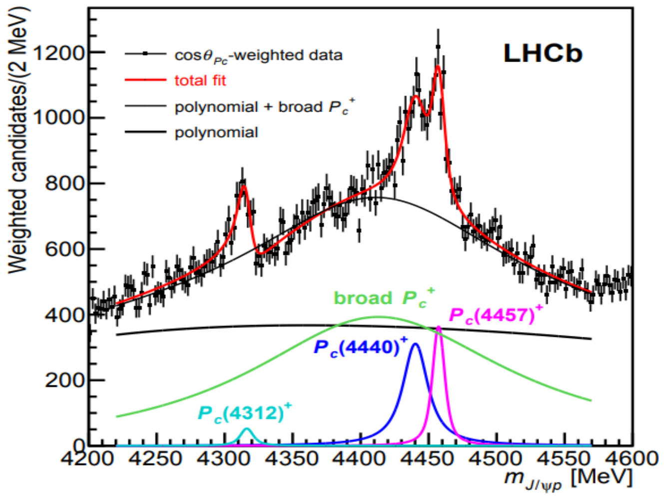
$P_c(4312)^+$ and $P_c(4457)^+$ are perfect candidates for the $\Sigma^+_c D_0$ and $\Sigma^+_c D^*_0$ bound states coupled mainly via π, ρ meson exchange.

$P_c(4440)^+$ with bound energy of ~20MeV is possibly another spin state of $\Sigma^+_c D^*_0$ molecule.



Existence of $P_c(4380)^+$ is under question. In case confirmed by amplitude analysis, it is not going to be described by molecular model and maybe interpreted as compact 5q state.
LHCb tried to include it into their background model (left plot).





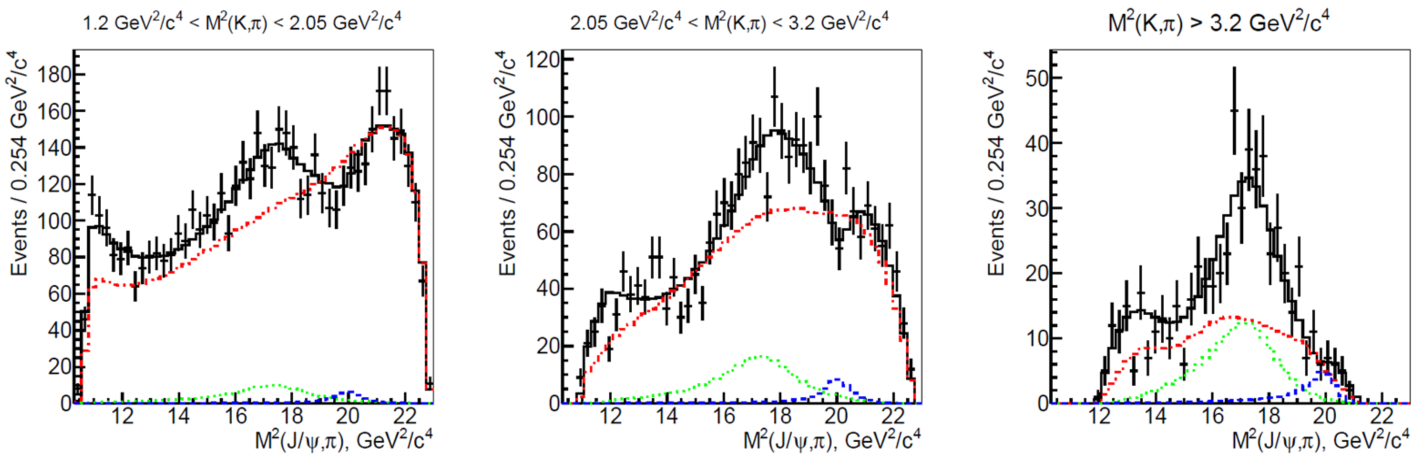
Another possible interpretation for narrow structures in J/ψp final states is triangular (rescattering) diagrams. However, it works well only for $P_c(4457)$. Still to be considered…

Natural predictions from QCD for new states are neutral pentaquarks (masses close to 4.3-4.4), strange pentaquarks, doubly strange pentaquarks, etc.

Z_c(4200) was discovered by BELLE collaboration with a significanceof 6.2σ in 2014. An amplitude analysis was performed to determine the parameters of this state:

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance (Wilks)	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

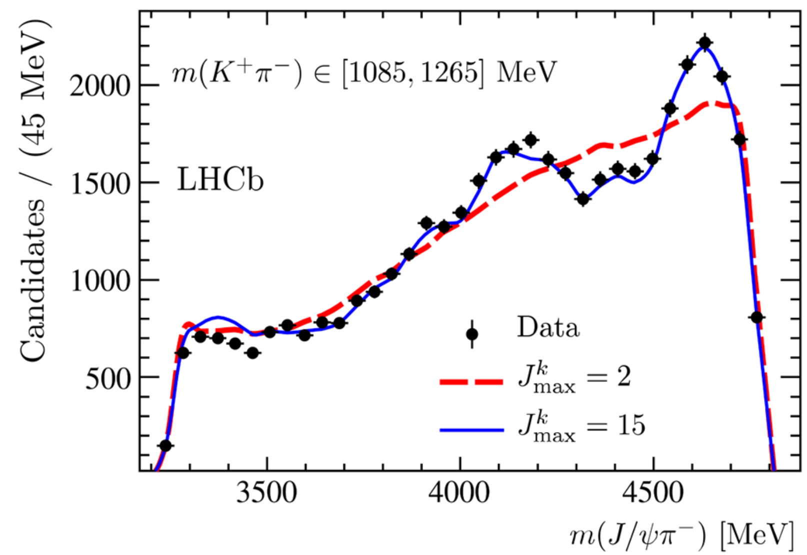
$$M = 4196^{+31+17}_{-29-13}\ \text{MeV}$$
$$\Gamma = 370^{+70+70}_{-70-132}\text{MeV}$$



10.1103/PhysRevD.90.112009

In 2008 BaBar collaboration performed model independent analysis of **B⁰→ J/ψKπ** decays to study Z_c(4430) state. No evidence of Z_c(4200) existence was found; ATLAS Run I studies gave hint on presence of Z_c contribution to B-meson decays;

In 2019 LHCb collaboration performed model independent analysis of **B⁰→ J/ψKπ** decays. They discovered an exotic structure near the mass m(J/ψπ) = 4200 MeV.



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Pentaquark studies: summary of systematic uncertainties

Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1}+P_{c2})$	$\Delta\phi$
Number of $\Lambda_b^0 \to J/\psi pK^-$ decays	$^{+1.8}_{-0.6}\%$	$^{+6.6}_{-9.2}\%$	$^{+1.6}_{-0.8}\%$	$^{+0.3}_{-0.0}\%$
Pentaquark modelling	$^{+21}_{-0}\%$	$^{+1}_{-22}\%$	$^{+8.7}_{-4.4}\%$	$^{+1.6}_{-0.0}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi pK^-$ modelling	$^{+14}_{-2}\%$	$^{+5}_{-44}\%$	$^{+9.2}_{-9.1}\%$	$^{+3.6}_{-1.6}\%$
Combinatorial background	$^{+0.7}_{-4.0}\%$	$^{+18}_{-5}\%$	$^{+4.2}_{-4.8}\%$	$^{+3.2}_{-0.0}\%$
B meson decays modelling	$^{+13}_{-25}\%$	$^{+28}_{-35}\%$	$^{+1.6}_{-9.3}\%$	$^{+0.5}_{-2.1}\%$
Total systematic uncertainty	$^{+28}_{-25}\%$	$^{+35}_{-61}\%$	$^{+14}_{-15}\%$	$^{+5.1}_{-2.7}\%$

Source	$m(P_{c1})$	$\Gamma(P_{c1})$	$m(P_{c2})$	$\Gamma(P_{c2})$
Number of $\Lambda_b^0 \to J/\psi pK^-$ decays	$^{+0.06}_{-0.03}\%$	$^{+3.5}_{-2.5}\%$	$^{+0.07}_{-0.04}\%$	$^{+7}_{-13}\%$
Pentaquark modelling	$^{+0.6}_{-0.0}\%$	$^{+18}_{-0}\%$	$^{+0.2}_{-0.0}\%$	$^{+0}_{-33}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi pK^-$ modelling	$^{+0.23}_{-0.05}\%$	$^{+9.2}_{-1.2}\%$	$^{+0.24}_{-0.02}\%$	$^{+2}_{-62}\%$
Combinatorial background	$^{+0.03}_{-0.15}\%$	$^{+0}_{-11}\%$	$^{+0.01}_{-0.17}\%$	$^{+22}_{-4}\%$
B meson decays modelling	$^{+0.24}_{-0.00}\%$	$^{+21}_{-21}\%$	$^{+0.27}_{-0.14}\%$	$^{+17}_{-57}\%$
Total systematic uncertainty	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

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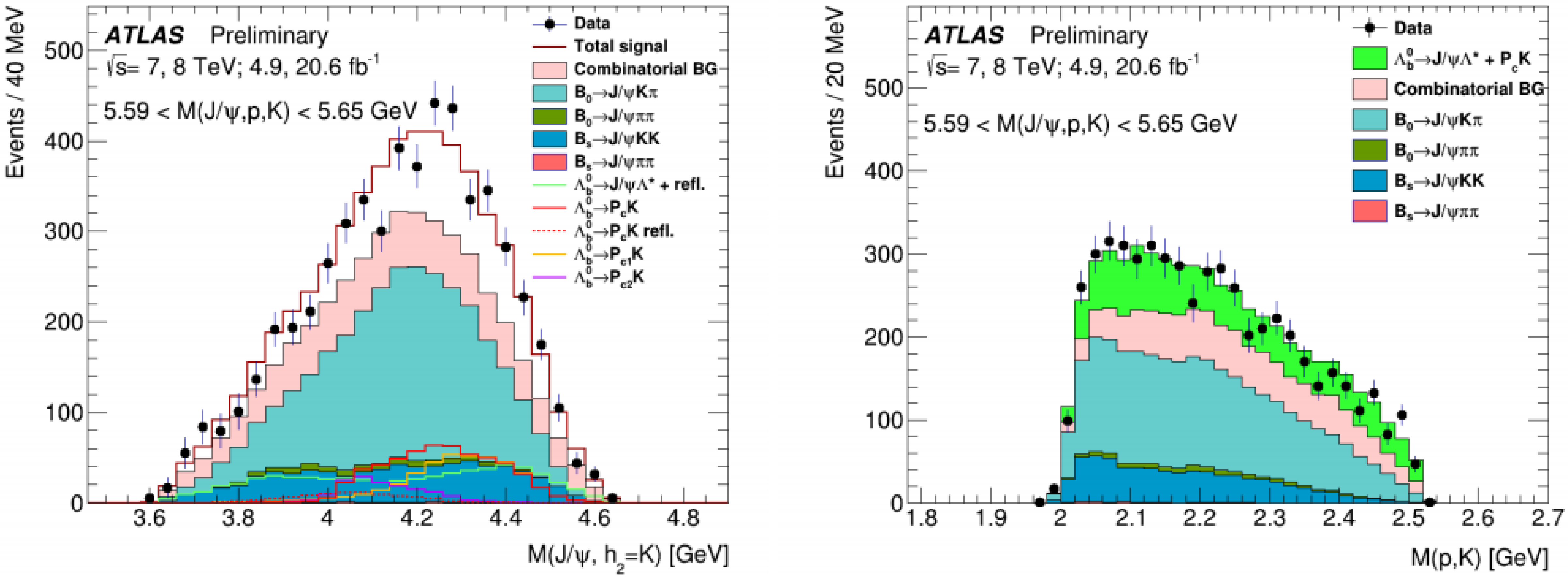

Control plots (2 pentaquark hypothesis) show good description of M(*J/ψK*) and M(*pK*) in the signal region.

Angular variables do not take part in fits due to complexity of background (esp. combinatorics) behavior.